

DISPERSAL AND MIXING OF OXYGEN IN THE INTERSTELLAR MEDIUM OF GAS-RICH GALAXIES

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Abstract

Stellar and nebular abundance indicators reveal that there exists significant abundance fluctuations in the interstellar medium (ISM) of gas-rich galaxies. It is shown that at the present observed solar level of $O/H \sim 6 \times 10^{-4}$, abundance differences of a factor of two, such as existing between the Sun and the nearby Orion Nebula, are many times larger than expected. We examine a variety of hydrodynamical processes operating at scales ranging from 1 pc to greater than 10 kpc, and show that the ISM should appear better homogenized chemically than it actually is: (i) on large galactic scales ($1 \geq l \geq 10$ kpc), turbulent diffusion of interstellar clouds in the shear flow of galactic differential rotation is able to wipe out azimuthal O/H fluctuations in less than 10^9 yrs; (ii) at the intermediate scale ($100 \geq l \geq 1000$ pc), cloud collisions and expanding supershells driven by evolving associations of massive stars, differential rotation and triggered star formation will re-distribute and mix gas efficiently in about 10^8 yrs; (iii) at small scales ($1 \geq l \geq 100$ pc), turbulent diffusion may be the dominant mechanism in cold clouds, while Rayleigh-Taylor and Kelvin-Helmholtz instabilities quickly develop in regions of gas ionized by massive stars, leading to full mixing in $\leq 2 \times 10^6$ yrs.

It is suggested that the relatively large O/H fluctuations observed in large disk galaxies may be due to retention, in sites favored by triggered star formation, of freshly enriched ejecta from SNR and supershells expanding in a differentially rotating disk, plus, possibly, *infall* of low metallicity material from individual clouds like high velocity clouds which splash on the disk on timecales shorter than the local mixing time. In low-mass galaxies, stimulated star formation is much less efficient, and the most effective mixing mechanisms are absent; the escape of newly enriched material due to galactic winds powered by the starburst events, the lack of large-scale stirring, and the long dormant phase between successive star forming episodes make possible the survival of large abundance discontinuities.

Keywords: galaxies: abundances – galaxies : evolution – galaxies: interstellar matter – galaxies: individual: I ZW 18 – interstellar medium: abundances – interstellar medium: kinematics and dynamics

1. Introduction

If one excludes the global radial abundance gradients observed in galactic disks, the ISM of the more massive galaxies appears on first examination relatively well-mixed. The chemical composition of the interstellar medium (ISM) in large spirals at a given radial distance appears not to vary much, but there are evidences that the ISM is not perfectly homogenized. O/H abundances derived from several indicators in large disk galaxies suggest that azimuthal variations could reach a factor of two (Belley & Roy 1992). However this is hard to quantify further because of the uncertainties underlying the procedures of nebular abundance derivations. Low-mass galaxies have very shallow global abundance gradients, and variations of O/H from one region to another in magellanic irregulars are moderate with fluctuations by a factor of about two (Dufour 1986), indicating that mixing of the ejecta from massive stars is not perfect in these systems either.

It is true that one does not see, in relatively massive galaxies, isolated pockets of ionized gas with $O/H = 1/50 O/H_{\odot}$ close to regions with $O/H = 2 O/H_{\odot}$; thus mixing processes appear quite effective. How effective they are is a relevant question since the sites of oxygen production could be correlated by triggered star formation, and give rise to significant spatial abundance fluctuations. The largest molecular clouds may survive the destructive photodissociation effect of the massive stars to which they give birth, and self-enrichment or auto-pollution of these clouds could occur (Gilmore 1989); however the survival of molecular clouds to evolving massive stars or to passage through spiral arms

remains questionable. On the other hand, the mixing in low-mass galaxies might be less efficient. This is strongly suggested by the largest known spatial discontinuity in heavy element abundances measured recently in the dwarf galaxy I Zw 18 by Kunth et al. (1994); employing high-resolution spectroscopy on GHRS-HST, they have derived the oxygen abundance in the cold cloud associated with the main star forming region of this well-known dwarf galaxy. While the ionized gas has $O/H \approx 1/30 O/H_{\odot}$, the measured O/H in the associated cold cloud is 30 times less, *i.e.* 1/1000 solar!

The importance of inhomogeneous chemical evolution of galactic disks has been emphasized recently by Malinie et al. (1993) who showed that chemical inhomogeneities

provide a much better fit to the abundance distribution function of G-dwarfs in the solar neighborhood. Poor mixing of the interstellar gas has also been proposed by Lennon et al. (1990) as an explanation for the observed discrepancies between the large-scale abundance gradients in our Galaxy deduced from H II regions (Shaver et al. 1983), and from hot stars (Gehren et al. 1985; Fitzsimmons et al. 1990); indeed B-type stars observed between about 5 and 15 kpc do *not* show systematic abundance variations.

In this paper, we wish to address the issue of dispersal and mixing of newly-formed elements in the interstellar medium by reviewing the various mechanisms which are responsible for the chemical homogenization of the interstellar gas, or the suppression of it both on local and galactic scales. This problem has been recently examined by Bateman & Larson (1993). They show that cloud motions may be the dominant mechanism for the dispersal of Fe. We will show that significant spatial abundance fluctuations exist in galaxy disks despite the apparent efficiency of mixing, and that these fluctuations are likely to be largest in very low-mass galaxies.

2. Evidence for abundance variations

Pagel (1993) has reviewed the abundances of heavy elements in the solar neighborhood, for which solar abundances are believed to be accurate to within ± 0.1 dex. The range of oxygen abundances is 0.3 dex as derived from ten different Galactic standards; how much of this is due to errors in the methods is not clear. For the ISM of the Galaxy, the abundance surveys of Shaver et al. (1983) and Fich & Sulkey (1991) are consistent with O/H variation up to a factor of 2 over a scale of about 1 kpc, best illustrated by the Sun-Orion Nebula well-known difference for the abundance of oxygen; the detailed study by Baldwin et al. (1991) gives O/H in the Orion Nebula as being 0.44 solar. The precision of abundance measurements in other galaxies is often hampered by the 0.2 dex uncertainty of the semi-empirical method of using the ratio of bright nebular lines. Nevertheless the dispersion at a given galactic radius of derived O/H values appears much larger than the experimental uncertainties. For the well-sampled galaxy NGC 2997, for example, azimuthal variations by a factor of two cannot be excluded (*cf.* Walsh & Roy

1989). Detailed studies of the chemical compositions of H II regions in the Magellanic Clouds are also consistent with overall abundance fluctuations by a factor of two (Dufour & Harlow 1977; Pagel et al. 1978).

Abundances have been measured in a large number of stars with a high degree of accuracy; these measurements reveal real scatter, *i.e.* which is larger than the observational errors and uncertainties (*cf.*) Edvardsson et al. 1993). The dispersion in the age-metallicity relation of nearby F stars (Carlberg et al. 1985), at least for the youngest stars, is indicative of interstellar abundance inhomogeneities. The scatter in stellar metallicities is very likely reflecting the original inhomogeneities of the interstellar gas (Gilmore 1989; François & Matteucci 1993). The existence of real scatter in the enrichment of the interstellar medium at any time is also seen in the age-metallicity relation for nearby clusters and stellar groups observed by Boesgaard (1989) who concluded that the apparent lack of an age-metallicity relationship indicates that the enrichment and mixing in the Galactic disk have not been uniform on timescales less than 10^9 yr. Rolleston et al. (1994) have derived stellar abundances of B stars belonging to clusters separated by distances of the order of 1 kpc and found abundance variations of a factor of five. From their extensive analysis of 189 nearby field F and G disk dwarfs, Edvardsson et al. (1993) find a residual scatter of probably 0.15 dex in $[\text{Fe}/\text{H}]$ at a given radius which remains to be explained by mechanisms other than simple chemical evolution. They also find that the α -group elements follow the iron group elements very closely; there is no significant scatter in $[\alpha/\text{Fe}]$ at a given age and galactocentric distance, which indicates that the nucleosynthetic products of the supernovae of different types are mixed locally in the interstellar gas.

Fluctuations by a factor of two correspond to $\delta\text{O}/\text{H} \sim 3 \times 10^{-4}$. How do these compare to what would be expected in a perfectly mixed disk? This calculation was done some time ago by Edmunds (1975), and it is interesting to repeat here his reasoning, using updated values for some of the physical parameters. We first assume that massive stars are randomly distributed in space and time in order to derive what would be the expected abundance fluctuations in a fully mixed ISM enriched only by *isolated* stars. We suppose then that every massive star develops a wind-blown bubble into which it

finally explodes as a supernova. The winds and explosions act as an effective mixing process (as we will see later) as well as providing new metals. From the $\Sigma - D$ diagram of Galactic supernova remnants, we estimate that each remnant reaches a radius of about 50 pc before it becomes undistinguishable from random structures in the disk (see Green 1984). Let us assume a simple homogeneous model of the Galaxy as a disk of $R = 12$ kpc and $z = 200$ pc; each wind bubble & supernova remnant will occupy a fractional volume $\sim 6 \times 10^{-6}$ of the disk. Assuming a constant SN rate of $1/100 \text{ yr}^{-1}$ over $\sim 10^{10}$ yrs, then at any point in the disk, an average of at least 580 SN events would have contributed by now to the metal enrichment of the ISM. We suppose that the metals ejected in the local ISM are fully mixed within the 50 pc radius during the lifetime of the remnant, and that the production of SN is randomly distributed throughout the disk. If n events contribute to give approximately the solar O/H abundance of 6.9×10^{-4} , then fluctuations of $\delta\text{O}/\text{H} \sim (\text{O}/\text{H}_\odot)/\sqrt{n} \sim 3 \times 10^{-5}$ would be expected. This is at least ten times smaller than observed, and considering our simplistic assumptions, the result is not surprising.

The above scenario is unlikely to be appropriate, because massive stars do not occur randomly; instead their formation is highly correlated in space and in time (see the review by Tenorio-Tagle & Bodenheimer 1988). This reduces the number of required enrichment events, and leads to an increase in the expected fluctuations. A visual inspection of any large gas-rich disk galaxy shows that, at any given time, of the order of $\sim 10^3$ massive star formation sites are active, and that they occupy $\sim 10\%$ of the volume of the disk. We assume that the star formation rate over the last 10^{10} years has been on average equal to the present one (Kennicutt 1994: private communication); the lifetime of each starburst is $\sim 2 \times 10^7$ yrs. Thus about $n = 50$ enrichment events would have taken place in any given volume of the disk. Although this number is much lower than in the random scenario, it does not explain the observed large O/H spatial fluctuations such as the Sun-Orion difference. Furthermore, this stationary scenario is also extreme, because it excludes the homogenizing effect of any mechanism capable of mixing the ejecta on scales larger than the individual H II regions. Consequently this discussion suggests that the observed fluctuations are many times larger than expected.

3. The mixing mechanisms for the gas

In this section, we review the various mechanisms responsible for mixing the ISM on various scales, and we show that there is a rich variety of processes capable of mixing the ISM fully and efficiently; these mechanisms are especially effective in the ionized gas of star forming regions. We investigate these mechanisms on three scales: large (1 - 10 kpc), intermediate (100 - 1000 pc) and small (0.1 - 100 pc).

3.1. Large-scale transport, differential rotation and azimuthal homogenizing

Like stars, gas clouds follow complex orbit patterns around the galaxy center. But as opposed to stars, clouds interact with each others; H I clouds are scattered isotropically when colliding with each other every 10^7 yrs (Spitzer 1978, Hausman 1981), and massive molecular clouds travel "straight" before being blown apart by massive stars. Roberts & Hausman (1984) have estimated the mean free path for molecular clouds to be in the range $l = 300 - 1000$ pc.

In a galaxy with differential rotation, motions around the center can be approximated by the superposition of a retrograde motion at angular frequency κ around a small ellipse with axis ratio 1/2, and prograde motion of the ellipse's center at angular frequency Ω around a circle (Binney & Tremaine 1987). For example, at the solar Galactic distance from the center, stars make about 1.3 oscillations in the radial direction to complete an orbit around the center in the time they need to complete their orbit, *i.e.* the epicyclic period is $\sim 1.8 \times 10^8$ yrs and stars make typical radial excursions of about 800 pc (Tayler 1993). Their radial excursions will appear, to an observer in circular orbit, as drifts at velocity v .

While stars keep their identity, clouds collide, merge or disperse. At a given point in the disk, one can imagine the various clouds as belonging to various orbits, criss-crossing the reference circular orbit. Because intercloud collision times take place on time scales much shorter than the orbital period, clouds loose their identity; individual parcels of gas will effectively change orbits and mix, while carried by the large scale flow around the galaxy. The net effect of cloud-cloud collisions is to act as a scattering process allowing clouds, fragments of clouds or parcels of gas to jump to different orbits describing each

their own rosette; their overall motions correspond to nonstationary turbulent transport in a shear flow, the shear being caused by the differential rotation of the galaxy. In such a case, diffusion is much more effective in the direction of the mean flow – direction of rotation – than in the directions perpendicular to it.

Turbulent transport in shear flows is well discussed by Tennekes and Lumley (1983). Consider a cartesian coordinate system centered at a given galactocentric point at distance R from the galaxy center. Let us take x_1 to be the direction tangential to the local circular orbit, and x_2 be the radial direction; we neglect effects perpendicular to the galactic plane. Let us suppose that the shear is due to differential rotation, and that orbiting clouds crossing the local circular orbit at a given point appear to come from random directions at rms velocity v ; v includes also the velocity dispersion of interstellar clouds. S is the radial gradient in velocity due to differential rotation; l is the mean free path of clouds. In the direction perpendicular to the orbit, the time to diffuse a length scale Δx_2 is given by stationary turbulence as

$$\tau_{x2} = \frac{\Delta x_2^2}{v l}.$$

But as a wandering parcel of gas moves in the x_2 radial direction, it moves into a region with a different mean velocity, so that it tends to move faster (or slower) than in a flow without shear. Consequently, in the orbital direction x_1 , the time to diffuse downstream and upstream is given (Tennekes & Lumley 1983) by

$$\tau_{x1} = \frac{\Delta x_1^{2/3}}{S^{2/3} v^{1/3} l^{1/3}}.$$

Thus the dispersion in the downstream and upstream direction (the direction of rotation) increases much faster than the dispersion perpendicular to it. This is the key to efficient azimuthal mixing in large disk galaxies with strong rotational velocity field.

Suppose star associations A and B being on the same orbit but diametrically opposed; at a given time, they suddenly enrich their neighborhood by exploding into supernovae. Using the last equation, we can calculate the time for collisions of clouds and differential rotation to diffuse their patches of enriched elements into each other (*i.e.* after travelling each 1/4 of a full orbit length). We suppose $S = 10 \text{ km s}^{-1} \text{ kpc}^{-1}$, $l = 300 \text{ pc}$, and $R_G = 10 \text{ kpc}$; we choose the value of v taking a typical star velocity with respect to the local

standard of rest; the latter defines the rotational speed of a hypothetical set of stars in precisely circular orbits. Taking $v \approx 10 \text{ km s}^{-1}$ (Mihalas & Binney 1981), the timescale for mixing clouds azimuthally in a galaxy is $\leq 10^9$ years. Consequently, galactic clouds orbiting at roughly the same galactocentric distance will fully mix in a small fraction of a Hubble time; this “epicyclic” mixing or dynamic diffusion is able to erase any azimuthal abundance variations in large disk galaxies.

3.1.1 Bar-induced mixing or the role of radial flows

Bars can induce strong radial flow in the interstellar gas of a galaxy (Lacey & Fall 1985, Struck-Marcell 1991, and Friedli & Benz (1993). Vila-Costas & Edmunds (1992), and Zaritsky, Kennicutt & Huchra (1994) have shown that global O/H gradients in intermediate and barred galaxies are shallower than gradients in normal galaxies. Martin & Roy (1994) have demonstrated that abundance gradients become flatter as the length or the ellipticity of the bar increases, *i.e.* the stronger the bar is, the flatter the abundance gradient becomes. The most direct explanation for this relation is that the strong radial flow associated with the bar acts as an efficient homogenizer of the chemical composition in the interstellar medium. Indeed numerical simulations by Friedli & Benz (1993) demonstrate that radial flows of several tens km s^{-1} can operate over a large fraction of the galaxy disk.

Magellanic systems display in general a strong bar and have flat abundance gradients (Edmunds & Roy 1993). We suggest that in such systems, differential rotation provides some degree of azimuthal homogenization, while the action of a bar would homogenize the gas radially on a timescale of less than 1 Gyr (Friedli, Benz & Kennicutt 1994).

3.2. Intermediate-scale transport

At the 100 - 1000 pc scale, intercloud collisions will be efficient contributors to mixing, since their mean free path is of the same order of scale. In addition, propagating star formation triggered by expanding shells driven by evolving massive stars could transport and mix interstellar gas *radially* over a galaxy disk. We discuss this scenario in more details because it may be the dominant diffusion process in galaxies with weak rotational field and continuous star formation.

McCray & Kafatos (1987) and Elmegreen (1992) review several cases of possible supershell-induced star formation. The close association of H II complexes with large H I holes observed in the Large Magellanic Cloud (Meaburn et al. 1991; Dopita et al. 1985), in Homberg II (Puche *et al.* 1992), IC 2574 (Martimbeau et al. 1994) and in NGC 6946 (Boulanger & Viallefond 1993) suggests that triggered star formation is taking place in expanding supershells. The net effect of this activity is the shuffling and re-distributing of the interstellar gas over relatively large scales.

In massive disk galaxies, Edmunds (1975) and Palouš et al. (1990) have shown that galactic rotation will shear the mixing volume of expanding interstellar bubbles into elliptical shape stretched in the direction of rotation about the galactic center, due to the streaming effect discussed in section 3.1. Typical amount of stretching are illustrated by the semi-minor and semi-major axes of the largest HI holes in M31 and M33 listed in Palouš et al. which are 190 ± 80 pc and 410 ± 300 pc over a typical time of $\sim 6.7 \times 10^7$ yrs. In other words, interstellar gas caught in an expanding supershell in a low mass galaxy will be displaced into an elliptically stretched expansion as shown by the simulations of Palouš et al. (1990). A question, discussed in section 4.1, is whether the new nucleosynthetic products polluting the expanding shells will fully disperse and mix on a larger scale *before* the parcels of gas of expanding superbubbles enter a new star formation episode again.

To quantify the transport of gas parcels through successive star forming episodes, we treat this as a diffusion problem in the case of homogeneous, stationary turbulence. We assume that most of the gas stays in the disk at all times, that is we exclude "breakout" or "blowout". Bursting out of the galaxy disk may happen in the cases of very large star formation events, where most of the momentum and kinetic energy escapes as a galactic wind, preventing runaway transformation of all the remaining gas into successive generations of stars. "Breakout" or "blowout" of superbubbles out of the galaxy disk, result in internal pressure decreasing so much that the accumulation of gas and formation of new clouds in the galaxy plane may stop. This is more likely to happen in the very low mass galaxies where escape velocities are only $\sim 100 \text{ km s}^{-1}$.

The collisional mean free path, λ , is the average distance traveled by a parcel of gas

before being caught in another star forming event which will drive its own supershell; it is assumed to correspond to the typical radius of H I holes which is ≈ 250 pc in small galaxies like Holmberg II (Puche et al. 1992), and 100 pc in large spirals like M 31 (Brinks & Bajaja 1986) or M 33 (Deul & Den Hartog 1990; Courtès et al. 1987). These values are larger than 50 pc used in section 2 for shells associated with single stars; this is because supershells are the results of evolving OB associations which contain many massive stars. The velocity, V , of the parcel of gas which is being propelled by a large expanding bubble is of the order of 40-50 km/s (Roy *etal.* 1991, 1992) during the early phase. This velocity drops to 5-10 km/s in the latter evolutionary stages of the expanding bubble (Puche *etal.* 1992). We use the higher value of velocity and we consider that the parcel of gas lingers at low velocity or remains quasi-stationary for a certain period of time that we will discuss below. If moving continuously all the time, a parcel of gas would random walk across the radius (R_G) of the galaxy in a time given by

$$\tau_d \approx \frac{R_G^2}{V \lambda}.$$

If $R_G = 4$ kpc (*e.g.* magellanic irregulars), $V = 45$ km s $^{-1}$, then $\tau \sim 1.5 \times 10^9$ years for a small galaxy ($\lambda \sim 250$ pc), and $\sim 10^{10}$ years in a large galaxy ($\lambda \sim 100$ pc; R_G 10 kpc).

This value of τ_d is a lower limit because a crucial aspect is missing. Triggered or supershell-induced star formation is not a continuous process, *i.e.* the parcel of gas may find itself in a new region of the interstellar medium where gravitational collapse, thus star formation, is not immediate. Some time may elapse before the onset of the next self-gravitation instability; this is the dormant phase. We need first to find what fraction of time a gas parcel spends in a starbursting region compared to the time spent in the dormant phase of stable H I filaments. From the above numbers, one could expect radial homogenization in less than a Hubble time in small galaxies, only if a parcel of gas spends more than 20% of its time in expanding supershells. The length of time spent by the parcel of gas in expanding supershells, *i.e.* the time spent moving around can be estimated from published numerical simulations. Igumentshchev *etal.* (1990) among others have modeled the evolution of large expanding shells generated by the collective winds and sequential supernovae from OB associations. Their calculated supershells, with radius and velocity

corresponding to observed ones, have lifetimes $t_{shell} = 13$ to 16 Myr; these are shorter than the apparent ages of the largest H I holes.

On the other hand, the dormant phase includes the duration of gravitationnal collapse and the period where the gas remains at rest; the later is very difficult to evaluate. We first discuss the timescale for collapse. Elmegreen (1992, 1994) has investigated triggered star formation along the perimeters of expanding giant shells by analyzing the radial and transverse gravitational collapse of such structures. The collapse of swept-up matter in an expanding and decelerating shell give rise to instabilities obeying a dispersion relation which allows to derive the time and the radius for collapse of clouds in a shell expanding with velocity V in a medium of a given pre-shell density; the time and distance for significant collapse are given by Elmegreen (1992, 1994) as

$$t_c = 103 \left(\frac{n_0}{\text{cm}^{-3}} M \right)^{-1/2} \text{ Myr},$$

and,

$$R_c = 176 M^{1/2} \left(\frac{c}{\text{km/s}} \right) \left(\frac{n_0}{\text{cm}^{-3}} \right)^{-1/2} \text{ pc},$$

where n_0 is the preshell number density, V is the instantaneous expansion speed, c is the rms velocity dispersion in the shell; for normal disk conditions, $M = V/c \approx 2$. (For the collapse of an expanding ring, the equations are similar and will be discussed in section 4.1). Assuming an average pre-shell number density of $\sim 10 \text{ cm}^{-3}$ (from $N(\text{HI})/d \approx 10^{21} \text{ cm}^{-2}/400 \text{ pc}$), $c = 10 \text{ km/s}$, we find $t_c = 20 \text{ Myr}$ and $R_c = 750 \text{ pc}$; this size is consistent with the radii of the largest H II complexes observed which are $\sim 0.5 \text{ kpc}$. We assume that the *minimum* duration of the dormant phase is given by t_c ; this time is of the same order as the duration of the expanding phase.

Therefore the crucial timescale is the time spent by the gas doing nothing. There is no direct way to estimate this, except to consider that large disk galaxies and magellanic irregulars have a constant SFR; thus the fractional area occupied by present day H II regions leads to an estimate of the fraction of time the gas spends in the dormant phase. Since H II regions cover about 10% of disk galaxies, the gas spend about 90% of its time not moving. Thus full radial mixing may take place in a time of the order of the Hubble time only in the smaller galaxies (magellanic irregulars and less massive system with

continuous star formation). Nevertheless superbubble expansion will contribute to mix gas on scales of $l \leq 1$ kpc in a timescale of 10^8 years in all galaxies where massive star formation is taking place.

3.3. Small-scale mixing

3.3.1 Turbulent diffusion

Turbulent diffusion takes place in ionized, neutral and molecular clouds. Turbulent diffusion is to be opposed to molecular diffusion, which is much slower and less efficient than eddy diffusivity acting when turbulent motions are present. In a medium with characteristic length scale L , *i.e.* motions are present of scales $\leq L$, and with a characteristic velocity u (defined as the rms velocity fluctuation in the medium), the time scale for diffusion is $\tau_{\text{diff}} \sim L/u$. Taking $u = 20 \text{ km s}^{-1}$ (Arsenault & Roy 1988) for the ionized gas, $u = 2 \text{ km s}^{-1}$ (Kulkarni & Heiles 1988) for the neutral gas clouds and $u = 0.5 \text{ km s}^{-1}$ (Falgarone & Phillips 1991) for the cold molecular clouds, one derives characteristic times for simple diffusion of 4×10^7 yrs, 4×10^8 yrs and 1.6×10^8 yrs for ionized, neutral and molecular clouds respectively; here we have assumed $L \sim 1$ kpc for ionized and neutral clouds, and $L \sim 100$ pc pour molecular clouds. For neutral and molecular gas, these timescales are much longer than the lifetimes (10^7 years) of the clouds themselves; thus inhomogeneities will not have the time to smooth out, before the destruction of the clouds by collision or star forming events. Thus homogenization must occur during the HII region lifetime to ensure mixing of individual clouds. It is likely that large abundances anomalies could survive for up to 10^9 years in the cold gas.

3.3.2 Fluid instabilities as mixing mechanisms

For H II regions, the development of Rayleigh-Taylor (R-T) and Kelvin-Helmholtz (K-H) instabilities takes place over a relatively short timescale and permits thorough mixing over the lifetime of star forming regions.

First several energetic phenomena associated with star formation events may give rise to instabilities in gas flows; they are related to mass losses from forming or evolving stars, and from moving stellar or nebular enveloppes. The development of these instabilities

makes the surrounding ISM fully turbulent, if the growth time of the instabilities is shorter than the lifetime of the object. Relevant phenomena are collimated outflows from young stars (Schwartz 1983), explosive ejection of matter associated with star formation (Allen & Burton 1993), champagne flows from H II regions bursting out of their parent molecular clouds (Tenorio-Tagle 1979), expanding supershells due to supernovae and stellar winds from star clusters, and superbubbles from evolving OB associations. The interaction of these dynamical structures with the ambient interstellar medium can give rise to the Rayleigh-Taylor and Kelvin-Helmholtz instabilities which develop over the surface of the moving components. The Rayleigh-Taylor instability leads to the fragmentation of the moving components, *i.e.* expanding shells break apart, and pieces of increasing size break away from the front of a collimated jet. The Kelvin-Helmholtz instability develops along the sides of the flow at the sheared surface of two fluids moving differentially with respect to each other. Once the waves have grown sufficiently, there is a shearing of the wave leading to vorticity, *i.e.* to a growing boundary of turbulent eddies.

The growth times of the surface waves, measured in terms of their e-folding times, can be calculated for an expanding shell driven by winds and supernovae. Chandrasekhar (1961; Shore 1992) give relations which can be used to calculate the growth time and the growth speed of the surface waves in the absence of a magnetic field; the relations for an incompressible fluid are applicable for the cases in hand. If a denser material with ρ_2 is accelerated into a less dense one with ρ_1 , some material from the two layers will be exchanged when a perturbation occurs at the interface; this will automatically happen when the density gradient is the opposite direction to the local acceleration. The upward and downward displacements of fluids will produce a change of potential energy equal to the total kinetic energy gained, *i.e.*

$$(\rho_2 - \rho_1) g \delta z = (\rho_2 + \rho_1) \delta z^2 \tau_{R-T}^{-2}$$

where τ_{R-T} is the growth rate of the disturbance and δz the displacement. Thus the growth time of Rayleigh-Taylor instabilities is simply given by

$$\tau_{R-T} = \left(\frac{\rho_1 + \rho_2}{\rho_2 - \rho_1} \right) (gk)^{-1/2}$$

where g is the effective gravity and k is the wavenumber of the largest instability. Let us

take the case of a large expanding shell pushed outward by evolving massive stars. For a continuous energy input, $R \propto t^{0.6}$ (Castor et al. 1975), and $g = \frac{2}{3} \frac{v^2}{R}$. Taking 100 pc as a typical radius of supershell, and $v = 40 \text{ km s}^{-1}$, $g \sim 3.6 \times 10^{-8} \text{ cm s}^{-2}$. For full fragmentation, we assume the largest disturbances to be the size of the thickness of the shell ($\sim 10 \text{ pc}$). For $\rho_2 \gg \rho_1$, $\tau_{R-T} \sim 10^6 \text{ yrs}$; the fragmentation time is comparable to the sound crossing time of the shell (Vishniac 1983). Thus R-T instabilities develop in expanding shells on a timescale at least ten times shorter than the lifetime of the parent OB associations.

A similar approach allows to derive the e-folding growth-time of the Kelvin-Helmholtz instability waves (see also Fleck 1984). When a fluid moves with differential velocity V with respect to another, Kelvin-Helmholtz instability waves will develop. A range of unstable wavelengths will grow, where (Chandrasekhar 1961)

$$\lambda_{max} = 2\pi V^2 (\rho_-/\rho_+) g^{-1}$$

where ρ_-/ρ_+ is the gas density ratio across the boundary and g is the acceleration at the boundary. The rise time for instability of wavelength λ is (Chandrasekhar 1961)

$$\tau_{K-H} \sim \frac{\lambda}{2\pi} (\rho_+/\rho_-)^{1/2} V^{-1}.$$

To allow complete mixing of existing inhomogeneities throughout a well-developed H II region, we compute the time for the wavelength of the largest disturbance to be or the order of the radius of a large H II region. Because of the square-root dependence on density, we make the approximation $n_+ \sim n_-$ within the nebular gas; for $\lambda \sim 100 \text{ pc}$, and $V = 10 \text{ km s}^{-1}$, $\tau_{K-H} = 1.5 \times 10^6 \text{ yrs}$, which again is much smaller than the lifetime of a typical OB association. With hot massive stars eroding the associated molecular cloud, jet generation by radiation-driven ionization fronts interacting with nonuniform neutral cloud edges (Sanford, Whitaker & Klein 1982) may add turbulent energy to the vortices generated by R-T and K-H instabilities. These considerations on instability growth show that abundance inhomogeneities introduced by evolving massive star forming regions should have the time to fully mix before the death of the H II region, even assuming that most new elements might be ejected only at the end of the lifetime of the stellar associations; evolutionary models of coeval OB associations indicate that most of the oxygen is ejected at ages between 4 and 10 millions years of age (Lequeux et al. 1981).

We summarize in Table 1 the various typical linear and time characteristic scales of processes responsible for mixing and erasing inhomogeneities in the gaseous interstellar medium of disk galaxies.

Table 1. Mixing Mechanisms in the Interstellar Medium

Scale (pc)	Mechanism	timescale (yr)	Remarks
$10^3 - 10^4$	– Turbulent transport in differential rotation	$< 10^9$	Azimuthal homogenization
	– Bar induced radial flows	10^9	Radial mixing
	– Triggered star formation from expanding supershell	$> 4 \times 10^9$	Radial and azimuthal homogenization (Sm, SBm)
$10^2 - 10^3$	– SNR and supershell in a differentially rotating disk	$< 10^8$	Intermediate scale mixing
$1 - 10^3$	– Turbulent diffusion*		
	• H II region	4×10^7	Mixing of fresh nuclei
	• H I cloud	4×10^8	Mixing within cold clouds
	• H ₂ cloud	1.6×10^9	Mixing of dormant clouds
	– R-T and K-H instabilities in star forming regions	1.5×10^6	Local mixing of fresh nuclei

(*) Timescale calculated for clouds of 1 kpc in diameter; H₂ clouds are more likely of the order 100 pc.

The main conclusions of our analysis are as follows: (i) Because of the hierarchical continuity in the linear and time scales of mixing processes (*i.e.* timescales of mechanisms mixing at small scales are much shorter than the those operating at larger scales), one

should expect a relatively well mixed interstellar medium in disk galaxies, *i.e.* one where $|\delta\text{O}/\text{H}| \ll 10^{-4}$ on scales $l \geq 1$ kpc. (ii) We reckon that the discrepancy between observed and expected abundance fluctuations is significantly large, observed variations being 5 - 10 times larger than expected ones (iii). Our analysis of the relative importance of large-scale and small-scale processes, *i.e.* cloud motions and collisions *vs.* turbulent processes, leads to obvious differences in mixing efficiency between dwarf and large galaxies. In particular, the weakness of the rotational velocity field in dwarf galaxies, the main agent for mixing neutral H I and molecular gas, and selective loss through galactic winds can lead to large abundance discontinuities in the smaller galaxies as already implied in section 3.2. Processes associated with massive star formation are extremely efficient at mixing hot and warm ionized gas; as a corollary, mixing is much less efficient in the cold neutral and molecular gas, mixing of these latter phases being done by galactic scale stirring. As a consequence, large abundance spatial fluctuations are more likely to be found in dwarf galaxies with long dormant phases between star forming episodes.

3.4 The large abundance discontinuity in I Zw 18 and the C:N:O problem

Because dwarf galaxies lack the stirring effect of large rotational velocity fields and because they have gone through very few massive star formation events, the main mixing processes associated with vigorous star formation are not operating in these systems. The presence of substantial amount of H I gas that is not rotationally supported in the faint dwarf galaxies is an unsolved puzzle (Lo et al. 1993). The case of the super-metal-poor low-mass galaxy I Zw 18 is particularly interesting to review.

Kunth and Sargent (1986) have proposed the view that giant H II regions are self-enriched. In such a case the new heavy elements ejecta originating from stellar winds and supernovae of type II (SNII) initially mix exclusively with the ionised gas in the H II zone, waiting for further mixing with the cold gas during the long interburst phase. Moreover as the authors note the closed-box model leads to over-enrichment of oxygen and only one burst is enough to produce the O/H in I Zw 18. Their suggestion has received a strong support from the recent abundance determination in the H I gas of I Zw 18 indicating that a previous burst could have occurred in the past leading to enrich the H I up to only 1/1000 the solar value after mixing in a time scale of about 10^9 years (Kunth et al. 1994), a timescale long enough to allow turbulent diffusion (section 3.3.1) to homogenize a cold cloud 1 kpc in diameter. Not only I Zw 18 is among the lowest abundance objects,

but it also displays the largest abundance discontinuity.

While N/O is proportional to O/H for relatively massive galaxies, low-mass (and oxygen poor) galaxies have on average smaller N/O ratios than oxygen rich ones, but some oxygen poor galaxies have the same N/O as oxygen rich ones; for $12 + \log \text{O/H}$ between 7.5 and 8.5, $\log \text{N/O}$ is scattered between -1.0 and -2.0. Some of the N/O scatter at low O/H is thought to be real, and N/O is certainly well measured in I Zw 18. Although Pagel *et al.* (1992) and Skillman & Kennicutt (1993) find a lower value of N/O than Dufour *et al.* (1988) in I Zw 18, $\log \text{N/O}$ is certainly *not* -2.0, -3.0 or less! To explain the observed scatter of N/O versus O/H for metal poor galaxies, Pilyugin (1992) built up models in which mixing is controlled by two processes: self-enrichment and galactic winds due to SNII. According to Pilyugin, each generation of stars contributes to the chemical enrichment of the ISM and metals mix into the whole galaxy. When starbursts begin, the N/O is unmodified, but as they evolve, large amounts of O are produced giving lower N/O ratios and an increase of O/H. On a short time scale, oxygen is enhanced more than the nitrogen because the bulk of nitrogen is produced by stars that live longer than those producing the bulk of oxygen. However the closed box model alone cannot explain the general N/O vs O/H trend nor the scatter.

A more complicated model must be assumed. Pilyugin introduces galactic stellar winds as proposed by Matteucci & Chiosi (1983) and Matteucci & Tosi (1985) where some oxygen-rich ejecta from SNII leave the galaxy before full mixing with the gas is completed (Russell et al. 1988; de Young and Gallagher 1990). By accounting for galactic stellar winds, better agreement with the scattered N/O vs O/H diagram is obtained. The key features in this modified model are that oxygen-poor galaxies are objects with efficient *enriched* galactic winds, and that they are in advanced stages of a star formation burst. Similar models developed by Marconi et al. (1994) reproduce the position of I Zw 18 using one single burst that started 5×10^7 years ago coupled with a high differential wind in which O is preferentially expelled compared to N. Evidence for this type of winds may be found in the nearby small starburst region NGC 2363 (Roy et al. 1992) where broad components in the main nebular lines probably arise from a superwind with velocity greater than 1000 km s^{-1} . The existence of a similar superwind in I Zw 18 is suggested by Skillman & Kennicutt (1993). Consequently the loss of metals through winds may be a key to understanding the chemical evolution of dwarf galaxies.

On the other hand Pantelaki and Clayton (1987) suggest a different scenario. Based on

the high ratios of N/O and C/O in I Zw 18, they rule out the possibility that the present starburst in I Zw 18 is the first one; moreover they shunt aside the possibility that the H II regions are contaminated by supernova ejecta from this very present burst. Instead they consider a situation in which previous bursts account for a hot gaseous phase ($T \sim 10^6$ K) surrounding a H I complex of small masses orbiting around the central stellar cores. These H I clouds eventually collide, giving rise to new starbursts (from initial abundances close to primordial) whereas the hot gas could contain large O and C concentrations; about one percent of this gas may have mixed with the H I. Each starburst spreads over 10^7 years and SNII disperse material into the hot medium. Between bursts, intermediate mass stars produce SNI and a lot of oxygen-free ejecta, thus O decreases in between bursts whereas C and N do not. However, Lo et al. (1993) have pointed out that the maintainance of a large volume filling factor of a hot phase in the ISM depends on a high frequency of supernovae which is unlikely for dwarf galaxies. Finally, from the spectroscopy of a new sample of very metal-poor galaxies (chosen from the SBS survey), Thuan et al. (1994) find a straight N/O value, with very little dispersion, and independent of the O/H value. This could be a further indication that C:N:O ratios in metal-poor galaxies undergoing their first bursts are indicative of genuine primary elements (see Maeder 1992 for a discussion of the C yield and Marconi et al. 1994 for the N prescription). In this case, the single burst hypothesis and the youth of I Zw 18 would not remain a problem.

4. Discussion

We have shown in the previous sections that small and medium-scale dynamical processes in the ionized medium, combined with turbulent transport in the shear flow of differential rotation should reduce azimuthal inhomogeneities in disk galaxies, in a timescale of less than 10^9 yrs, to a level where they could hardly be measured with present techniques. In low-mass galaxies with little rotational shear, such mechanisms are much less efficient than in large disk galaxies, or do not operate at all, and large abundance discontinuities are likely to survive more than 10^9 years.

Assuming that the amplitude of observed O/H abundance fluctuations in large disk galaxies and magellanic irregulars are significantly larger than expected, we propose two complementary effects that may act to build up, or maintain, large abundance fluctuations in the ISM. The first effect is one of retention of newly enriched material in regions prone to undergo relatively quickly successive episodes of star formation. Fluctuations can

be created by localized bursts of star formation (whether or not triggering is involved). Implicit to sequential star formation is some confinement of stellar ejecta: newly produced elements are “trapped” in SN remnants and superbubbles, which are the privileged sites for new star formation because their higher densities make them prone to quicker collapse under gravitational instability. The second effect, as suggested by Edvardsson *etal.* (1993), is infall of relatively unprocessed gas, where the timescale of infall events is shorter than the epicyclic mixing time described in section 3.1. Let us examine each of these mechanisms.

4.1 Abundance inhomogeneities from triggered star formation?

Franco (1992) has shown that shear due to differential rotation has two important effects on expanding supershells: first, it distorts the shape of the remnant as illustrated by the numerical simulation of Paloš et al. (1990), and, second, it changes the distribution of mass due to the epicyclic motion of the particles in the expanding shell which creates particle flow toward the tips of the distorted remnant, where the shell mass tends to be accumulated; these preferentially enriched tips then become the preferred locations for molecular cloud production and star-forming clouds. The consequence of triggered star formation is that some clouds spent much less time in the dormant phase, thus newly ejected elements are retained for the to-be-borne stars.

The amplitude of O/H fluctuations will depend on the relative importance of *stimulated* star formation with respect to *spontaneous* star formation driven by gravitational instabilities. This requires the time scale for gravitational instability to be much shorter for expanding gas than for stationary gas. Following Elmegreen (1994), this implies $(G\rho_0 M^2)^{-1/2} \ll (G\rho_0)^{-1/2}$ for expanding rings, or $(G\rho_0 M)^{-1/2} \ll (G\rho_0)^{-1/2}$ for expanding shells. We recall that $M = V/c$ is a dimensionless quantity which measures the ring or shell compression or thickness; when M is large, the shell is thin and the collapse is rapid because of high density. Once formed the lifetime of an expanding shell (or ring) driven by evolving associations of massive stars is determined by the time for Coriolis force due to galactic rotation and shear to distort and erase the blown cavity (Edmunds 1975); this time is $\tau_{\text{Coriolis}} = 2.5/\kappa$ (Paloš et al. 1990; Franco 1992), κ being the epicyclic frequency. For the solar neighborhood, $\tau_{\text{Coriolis}} \sim 10^8$ yr. We showed in section 3.2 that gravitational collapse of expanding shells *can* take place in much less than this time; thus it is plausible to consider a sequence of star forming activities involving a same given

portion of the disk. To explain large abundance fluctuations, one requires some portions of a galaxy disk to obey (Elmegreen 1994)

$$\frac{1.5}{(G\rho_0)^{1/2}M} < \frac{2.5}{\kappa}, \quad \text{for rings}$$

or

$$\frac{1.25}{(G\rho_0 M)^{1/2}} < \frac{2.5}{\kappa}, \quad \text{for shells.}$$

These relations must be obeyed for each episode of stimulated star formation; a whole sequence of triggered episodes of massive star formation may last longer than τ_{Coriolis} .

Furthermore, we suggest that the *ring* relation of above is applicable to the disks of massive galaxies because most of the accumulated material originally in the interior of the blown cavity will stay in the galactic plane; the *shell* relation on the other hand, is applicable to low-mass galaxies, where the restoring force is weaker due to the shallow gravitational potential and material can move to the halo easily. Thus for the same parameter values, triggered star formation takes a longer time (by a factor $M^{1/2}$) to occur in expanding shells compared to rings. In addition, the compression of an expanding shell would be weaker in metal deficient objects like I Zw 18 because of less efficient cooling; the shells in dwarf galaxies are then thick and their corresponding values of M small; this delays their collapse further. Furthermore, dwarf galaxies are “fat” systems with a very clumpy H I distribution (Lo et al. 1993); evolving superbubbles from OB association will grow faster in directions with the lowest column densities to the intergalactic medium. Thus for superbubbles expanding in low-mass galaxies, most of the internal pressure may be released through a chimney or a blowout (Ikeuchi 1987). The blowout phenomenon is a transformation of internal energy to kinetic energy, and the blowout power corresponds to a reduced mechanical power in the plane of the galaxy (Schiano 1985). The C:N:O abundance ratios in I Zw 18, as we have shown, are certainly indicative of losses through some sort of wind. To summarize, triggered star formation is not effective in very low mass systems such as I Zw 18 because (i) the time for gravitational collapse of an expanding spherical shell is longer than to collapse a ring, (ii) low metallicity results in lower compression of shells (small M), thus again in slower collapse, and (iii) the loss of material by galactic wind and of internal pressure through blowout or chimney quenches the piston effect in the ISM of the galaxy.

In larger and more metal-rich disk galaxies, expansion as a ring, high compression and low probability of blowout make triggered star formation an effective process. To

estimate the amplitude of abundance fluctuations built up through retention of enriched gas in sequential events of stimulated star formation, we assume that nucleosynthetic products ejected in the ISM have been well-mixed by now, *except* for those injected in the last $1 - 2 \times 10^9$ yrs. We associate the region with the highest O/H with regions where *both* stimulated and spontaneous star formation have contributed, while regions with the lowest O/H correspond to regions affected by spontaneous star formation only. In our scenario, we do consider that most star formation in disks is spontaneous on galactic scale and lifetime, but that some pockets can undergo vigorous sequences of starbursts. If we do not allow the new nucleosynthetic products to quickly mix with the larger-scale surrounding, the most extreme discrepancies of abundances will be observed between the portions enriched by both spontaneous and stimulated on one hand, and the regions enriched only from spontaneous star formation on the other hand. The difference can be described approximately as

$$\frac{O/H_{max}}{O/H_{min}} = [t_1 + t_2 (SF_{stim}/SF_{spon})] \tau_G^{-1},$$

where t_1 is the duration of galactic enrichment period whose products are fully mixed, and t_2 is the duration where mixing has not had time yet to take place; τ_G is the Galaxy age (10^{10} yrs). Evidently, the shorter t_2 is, the higher the ratio SF_{stim}/SF_{spon} must be. For t_2 of 2×10^9 , 10^9 and 10^8 yrs, the ratio is 5, 10 and 50 to explain variation by a factor of 2 in O/H this way. We suggest that a period of $t_2 = 10^9$ yrs is plausible; remember that we consider the factor of 2 abundance discontinuity to be an extreme; one can imagine a given group of clouds caught, during the last 10^9 yrs (four Galactic rotations) in a sequence about 10 episodes of star formation while some other group, at an equivalent galactocentric distance, would have undergone only one or two such events. We exclude $t_2 = 2 \times 10^9$ yrs because it is difficult for groups of clouds to keep their identity over such a long duration (see section 3.1); shorter periods such as $t_2 = 10^8$ yrs are also excluded because of the extreme rate of stimulated SF required.

4.2 Infall and “splatter” as the source of inhomogeneities

Infall of low-metallicity material on the galactic disk is also an attractive mechanism to account for the presence of large abundance fluctuations in disk galaxies. First infall solves other problems related to galactic chemical evolution (*e.g.* the G-dwarf problem). Second it is a simple and straightforward way to explain why the metal abundance of

star clusters located within 1 kpc of each other can differ by as much as a factor of 5 in abundances (Rolleston et al. 1994), why the oxygen abundance in the Orion Nebula is only 1/2 solar while being about 4.5 billion years younger than our Sun, and why there is so much observed scatter of $[\text{Fe}/\text{H}]$ in nearby clusters.

Mayor & Vigroux (1981) and Pitts & Tayler (1989) have discussed in detailed the effect of infall of matter on the dynamics and chemistry of galaxy disks; mass accretion rates of $\leq 1 M_{\odot}/\text{yr}$ are usually implied for the whole galaxy. Franco et al. (1988) have suggested that the Orion and Monoceros molecular cloud complexes result from the interaction of high-velocity clouds and the disk of the Galaxy. Although falling gas may be in large part recycled material participating in the circulation between the halo and the disk, there are evidences that some high-velocity clouds may be of extragalactic origin (Mirabel 1989). Some of these have low abundances, as demonstrated by Kunth et al. (1994) who measured O/H and Si/H to be about 1/10 the abundance of the local interstellar gas in a Galactic high velocity cloud. When impacting on the disk, the colliding remnants would give rise to molecular cloud formation followed by the birth of massive stars (Franco et al. 1988). The stars and the ionized gas resulting from such collisions would then display anormal abundances compared to the expected abundances from the normally inferred history of star formation at that galactocentric distance; it is certainly easy to produce regions with half the solar abundances like Orion. If the Magellanic Stream is a source of infall, the abundance in the LMC being about 1/3 solar, this may also give rise to local abundance anomalies depending on where the accreting gas impacts on the Galaxy.

5. Conclusion

We have reviewed various stellar and interstellar abundance indicators of metallicity of the interstellar medium of gas-rich galaxies: there is a growing body of observationnal data showing that there exist significant spatial abundance fluctuations; the amplitude of the observed fluctuations appears 5 - 10 times larger than expected, given the apparent high efficiency of mixing in the interstellar medium of most galaxies. Indeed, examining the processes capable of moving, re-distributing and mixing the ISM, we have shown that turbulent transport in the shear flow of a differentially rotating disk will efficiently mix the ISM of large disk galaxies so that azimuthal inhomogeneities will persist less than 10^9 years. On scales of 1 kpc or less, mixing is achieved in good part by gas motions generated by star formation. The absence of abundance gradient magellanic irregulars is

probably due to the radial homogenizing action of a bar.

To explain the apparent large amplitude of spatial abundance fluctuations in massive disk galaxies, we suggest retention of enriched ejecta in evolving structures favored by stimulated or triggered star formation, and possibly infall of clouds with low abundance content of metals. We have also shown that the largest fluctuations are expected in low mass galaxies. This is clearly illustrated by the largest abundance discontinuity found in the low-mass galaxy I Zw 18; it is explained by the long dormancy between episodes of star formation, due the inefficiency of triggered star formation and the lack of powerful large-scale stirring mechanisms like differential rotation.

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References

- Allen, D. A., Burton, M. G., 1993, *Nature*, 363, 54
- Arsenault, R., Roy, J.-R., 1988, *A&A*, 201, 199
- Baldwin, J. A., Ferland, G. J., Martin, P. G., Corbin, M. R., Cota, S. A., Peterson, B. M., Slettebak, A., 1991, *ApJ*, 374, 580
- Bateman, N. P. T., Larson, R. B., 1993, *ApJ*, 407, 634
- Belley, J., Roy, J.-R., 1992, *ApJS*, 78, 61
- Binney, J., & Tremaine, S., 1987, *Galactic Dynamics*. Princeton University Press, Princeton
- Boesgaard, A. M. 1989, *ApJ*, 336, 798
- Boulanger, F., Viallefond, F., 1992, *A&A*, 266, 37
- Brinks, E., Bajaja, E., 1986, *A&A*, 169, 14
- Carlberg, R. G., Dawson, P. C., Hsu, T., Vandenberg, D. A., 1985, *ApJ*, 294, 674
- Castor, J., McCray, R., Weaver, R., 1975, *ApJ*, 200, L107
- Chandrasekhar, S. 1961, *Hydrodynamic and Hydromagnetic Stability*. Oxford University Press, Oxford
- Courtès, G., Petit, H., Sivan, J.-P., Dodonov, S., Petit, M. 1987, *A&A*, 174, 28
- Deul, E. R., Den Hartog, R. H., 1990, *A&A*, 229, 362
- de Young, D.S., Gallagher III, J.S., 1990, *ApJ*, 356, L15
- Dopita, M., Mathewson, D. S., Ford, V. L., 1985, *ApJ*, 297, 599
- Dufour, R. J. 1986, *PASP*, 98, 1025
- Dufour, R. J., Harlow, W. V., 1977, *ApJ*, 216, 706

- Dufour, R. J., Garnett, D. R., Shields, G. A., 1988, ApJ, 332, 752
- Edmunds, M. G., 1975, ApSS, 32, 483
- Edmunds, M. G., Roy, J.-R., 1993, MNRAS, 261, L17
- Edvardsson, B., Andersen, J., Gustafsson, Lambert, D. L., Nissen, P. E., Tomkin, J., 1993, A&A, 275, 101
- Elmegreen B. G. 1992, In: Tenorio-Tagle, G., Prieto, M., Sanchez, F. (eds.) Star Formation in Stellar Systems. Cambridge Univ. Press, Cambridge, p. 381
- Elmegreen, B. G. 1994, ApJ May 20
- Falgarone, E., Phillips, T. O., 1991, In: Falgarone, E. *et al.* (eds.) Proc. IAU Symp. 147, Fragmentation of Molecular Clouds and Star Formation Reidel, Dordrecht, p. 119
- Fich, M., Silkey, M., 1991, ApJ, 366, 107
- Fitzsimmons, A., Brown, P. J. F., Dufton, P. L., Lennon, D. J., 1990, A&A, 232, 437
- Fleck, R. C., 1984, AJ, 89, 506
- Franco, J., 1992, In: Tenorio-Tagle, G., Prieto, M., and Sanchez, F. (eds.) Star Formation in Stellar Systems, Cambridge Univ. Press, Cambridge, p. 515
- Franco, J., Tenorio-Tagle, G., Bodenheimer, P., Różyczka, Mirabel, F., 1988, ApJ, 333, 826
- François, P., Matteucci, F., 1993, A&A, 280, 136
- Friedli, D., Benz, W., 1993, A&A, 268, 65
- Friedli, D., Benz, W., Kennicutt, R., 1994, ApJL, submitted
- Gehren, T., Nissen, P. E., Kudritzki, R. P., Butler, K., 1985, In: Proc. ESO Workshop on Production and Distribution of CNO Elements, ESO, Garching, p. 171

- Gilmore, G., 1989, In: Buser, R., King, I. R. (eds.) *The Milky Way as a Galaxy*. Univ. Science Books, Mill Valley Ca., p. 281
- Green, D. A., 1984, *MNRAS*, 209, 449
- Hausman, M. A., 1981, *ApJ*, 245, 72
- Igumentshchev, I. V., Shustov, B. M., Tutukov, A. V., 1990, *A&A*, 234, 396
- Ikeuchi, S., 1987, In: Thuan, T. X., Montmerle, T., Tran Thanh Van, J. (eds.) *Starbursts and Galaxy Evolution*, Editions Frontières, Gif-sur-Yvette, p. 27
- Kennicutt, R. C., 1992, In: Tenorio-Tagle, G., Prieto, M., Sanche, F. (eds.) *Star Formation in Stellar Systems*, Cambridge Univ. Press, Cambridge, p. 191
- Kulkarni, S. R., Heiles, C. 1988, In: Verschuur, G. L., K. I. Kellerman, (eds.) *Galactic and Extragalactic Radioastronomy*. Springer-Verlag, Berlin, p. 95
- Kunth, D., Sargent, W. L. W., 1986, *ApJ*, 300, 496
- Kunth, D., Lequeux, J., Sargent, W. L. W., Viallefond, F., 1994, *A&A*, 282, 709
- Lacey, C. G., Fall, S. M., 1985, *ApJ*, 240, 154
- Lennon, D. J., Dufton, P. L., Fitzsimmons, A., Gehren, T., Nissen, P. E., 1990, *A&A*, 240, 349
- Lequeux, J., Maucherat-Joubert, M., Deharveng, J. M., Kunth, D., 1981, *A&A*, 103, 305
- Lo, K. Y., Sargent, W. L. W., Young, K., 1993, *AJ*, 106, 507
- Maeder, A., 1992, *A&A*, 264, 105
- Malinie, G., Hartmann, D. H., Clayton, D. D., Mathews, G. J., 1993, *ApJ*, 413, 633
- Marconi, G., Matteucci, F., Tosi, M., 1994, *MNRAS* in press
- Martimbeau, N., Carignan, C., Roy, J.-R., 1994, *AJ*, 107, 543
- Martin, P., Roy, J.-R., 1994, *ApJ*, 424, 599

- Matteucci, F., Chiosi, C., 1983 A&A, 123, 121
- Matteucci, F., Tosi, M., 1985, MNRAS, 217, 391
- Mayor, M., Vigroux, L., 1981, AA, 98, 1
- McCray, R. Kafatos, M., 1987, ApJ, 317, 190
- Meaburn, J., Solomos, N., Laspias, V., Goudis, C., 1989, A&A, 225, 497
- Mihalas, D., Binney, J., 1981, Galactic Astronomy, W. H. Freeman and Co., San Francisco
- Mirabel, I. F., 1989, In: Tenorio-Tagle, G., Moles, M., Melnick, J. (eds.) Structure and Dynamics of the Interstellar Medium. Springer-Verlag. Berlin, p. 396
- Pagel, B. E. J., 1993, eds. Baschek, B., Klare, G., Lequeux, J. (eds.) New Aspects of Magellanic Cloud Research. Springer-Verlag, Berlin, p. 330
- Pagel, B. E. J., Edmunds, M. G., Fosbury, R. A. E., Webster, B. L., 1978, MNRAS, 184, 569
- Pagel, B. E. J., Simonson, E. A., Terlevich, R. J., Edmunds, M. G., 1992, MNRAS, 255, 325
- Palořs, J., Franco, J., Tenorio-Tagle, G., 1990, A&A, 227, 175
- Pantelaki, I., Clayton, D., 1987, In: Thuan, T. X., Montmerle, T., Tran Thanh Van, J. (eds.) Starbursts and galaxy evolution. Editions Frontieres, Gif-sur-Yvette, p.145
- Pilyugin, L.S., 1992, A&A, 260, 58
- Pitts, E., Tayler, R. J., 1989, MNRAS, 240, 373
- Puche, D., Westpfahl, D., Brinks, E., Roy, J.-R., 1992, AJ, 103, 1841
- Roberts, W. M. & Hausman, M. A., 1984, ApJ, 277, 744
- Rolleston, W. R. J., Dufton, P. L., Fitzsimmons, A., 1994, A&A, 284, 72

- Roy, J.-R., Boulesteix, J., Joncas, G., Grundseth, B., 1991, *ApJ*, 367, 141
- Roy, J.-R., Aubé, M., McCall, M. L., Dufour, R. J., 1992, *ApJ*, 386, 498
- Russell S.C., Bessell M.S., Dopita, M.A., 1988, In: Cayrel de Strobel, G., Spite, M. (eds.)
IAU Symp. 132, The Impact of Very High S/N Spectroscopy on Stellar Physics.
Reidel, Dordrecht, p. 545
- Sandford, M. J., II, Whitaker, R. W., Klein, R. I., 1982, *ApJ*, 260, 183
- Schiano, A. V. R., 1985, *ApJ*, 299, 24
- Schwartz, R. D. 1983, *ARAA*, 21, 209
- Sellwood, J. A., Wilkinson, A., 1993, *Reports on Progress in Physics*, 56, 173
- Shaver, P. A., McGee, R. X., Newton, L. M., Danks, A. C., Pottasch, S. R., 1983,
MNRAS, 204, 53
- Shore, S. N., 1992, *An Introduction to Astrophysical Hydrodynamics*, Academic Press,
Inc., San Diego
- Skillman, E. D., Kennicutt, R. C., 1993, *ApJ*, 411, 655
- Spitzer, L., 1978, *Physical Processes in the Interstellar Medium*, Wiley-Interscience, New
York
- Struck-Marcell, C., 1991, *ApJ*, 368, 348
- Tayler, R. J., 1993, *Galaxies: Structure and Evolution*, Cambridge University Press,
Cambridge
- Tennekes, H. & Lumley, J. L., 1983, *A First Course in Turbulence*, The MIT Press,
Cambridge, Mass.
- Tenorio-Tagle, G., 1979, *A&A*, 71, 59
- Tenorio-Tagle, G., Bodenheimer, P., 1988, *ARAA*, 26, 145

- Thuan, T. X., Izotov, Y. I., Lipovetsky, V. A., Pustilnik, S. A., 1994, In: ESO/OHP Workshop on Dwar Galaxies, in press
- Vila-Costas, M. B., Edmunds, M. G., 1992, MNRAS, 259, 121
- Vishniac, E. T., 1983, ApJ, 274, 125
- Walsh, J. R., Roy, J.-R., 1989, ApJ, 341, 722
- Zaritsky, D., Kennicutt, R. C., Huchra, J. P., 1994, ApJ, 420, 87